PB89-205124

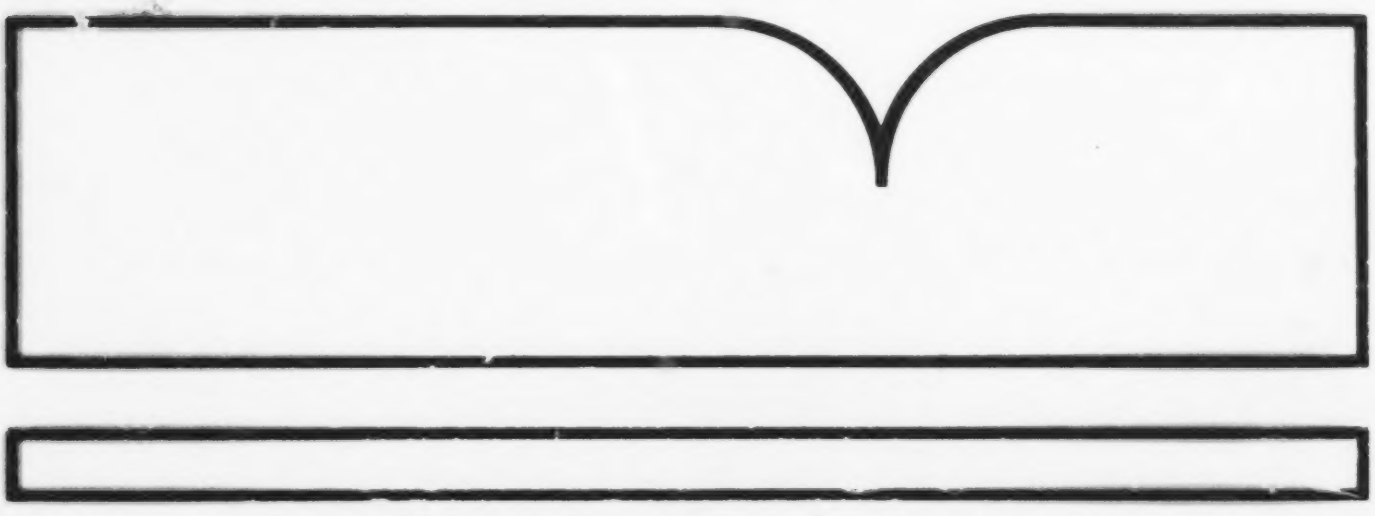
Injury and Yield Response of Cotton to Chronic Doses of Ozone and Soil Moisture Deficit

(U.S.) Agricultural Research Service, Beltsville, MD

Prepared for:

Corvallis Environmental Research Lab., OR

1988



U.S. Department of Commerce
National Technical Information Service
NTIS

ERL-COR- 835J

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before complete)

1. REPORT NO. EPA/600/J-88/304	2.
3. PB89-205124	
4. TITLE AND SUBTITLE: Injury and yield response of cotton to chronic doses of ozone and soil moisture deficit	5. REPORT DATE
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S): A.S Heagle, J.E. Miller, W.W. Heck and R.P. Patterson	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS: USDA-ARS & North Carolina State Univ., Raleigh, NC	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO. IAG No. DW12931347
12. SPONSORING AGENCY NAME AND ADDRESS: US Environmental Protection Agency, Environmental Research Laboratory, 200 SW 35th Street, Corvallis, OR 97333	13. TYPE OF REPORT AND PERIOD COVERED: Journal Article
	14. SPONSORING AGENCY CODE: EPA/600/2
15. SUPPLEMENTARY NOTES: J. Environ. Qual. 17(4):627-635	

16. ABSTRACT

Plant response to ozone (O_3) is known to be modified by soil moisture deficit, which occurs in varying degrees during most growing seasons. Thus, we examined the response of cotton (*Gossypium hirsutum* L. 'McNair 235') to different levels of seasonal stress by O_3 when grown at two soil moisture levels. The cotton was exposed for 12 h d^{-1} in open-top field chambers to five O_3 doses (seasonal 12 h d^{-1} means from 0.020 to 0.074 $\mu L\ L^{-1}$) under well-watered (WW) conditions or under water-stressed (WS) conditions with periodic cycles of low soil moisture. Exposures began when the fifth leaves were expanding and continued for 124 d when most leaves were chlorotic or had abscised. Ozone caused significant yield loss in WW plots but not in WS plots. Based on estimates from polynomial regression analysis, ambient O_3 (seasonal 12 h d^{-1} mean of 0.044 $\mu L\ L^{-1}$) caused a yield decrease of 19% in the WW plots compared to the O_3 level in our charcoal-filtered air plots (seasonal 12 h d^{-1} mean of 0.022 $\mu L\ L^{-1}$). The comparable estimate for data from the WS plot was 7%, but this regression was not statistically significant. Results indicate that soil moisture deficit can decrease the impact of O_3 on cotton yield.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

18. DISTRIBUTION STATEMENT: Release to Public	19. SECURITY CLASS (This Report): Unclassified	21. NO. OF PAGES: 11
	20. SECURITY CLASS (This page): Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

Doll, E.C., S.D. Merrill, and G.A. Halvorson. 1984. Soil replacement for reclamation of stripmined lands in North Dakota. Bull. 514. North Dakota Land Reclamation Center, Mandan, ND.
Environment Canada. 1982. Canadian climate normals. Vol. 3. Precipitation 1951–1980. p. 104. Atmospheric Environment Service, Ottawa, Ont.
Halvorson, G.A., A. Bauer, S.A. Schroeder, and S.W. Melsted. 1987. Corn and wheat response to topsoil thickness and phosphorus on reclaimed land. J. Environ. Qual. 16:73–76.
Hargis, N.E., and E.F. Redente. 1984. Soil handling for surface mine reclamation. J. Soil Water Conserv. 39:300–305.
Hausenbuiller, R.L. 1985. Soil water management. p. 195. *In* Soil science: Principles and practices. 3rd ed. Wm. C. Brown Publ., Dubuque, IA.
Howse, K.R. 1981. A technique for using permanent neutron meter access tubes in cultivated soils. Exp. Agric. 17:265–269.
McKeague, J.A. (ed.). 1978. Manual on soil sampling and methods of analysis. 2nd ed. Can. Soc. Soil Sci., Otawwa, ON, p. 15, 69–71, 155.
Merrill, S.D., E.J. Doering, and J.F. Power. 1980. Changes of sodicity and salinity in soils reconstructed on strip-mined land. North Dakota Farm Res. 37:13–16.
Merrill, S.D., E.J. Doering, J.F. Power, and F.M. Sandoval. 1983. Sodium movement in soil-minespoil profiles: Diffusion and convection. Soil Sci. 136:308–316.
Merrill, S.D., S.J. Smith, and J.F. Power. 1985. Effect of disturbed soil thickness on soil water use and movement under perennial grass. Soil Sci. Soc. Am. J. 49:196–202.
Nakayama, F.S., and R.J. Reginato. 1982. Simplifying neutron moisture meter calibrations. Soil Sci. 133:48.
Power, J.F., F.M. Sandoval, and R.E. Ries. 1979. Topsoil-subsoil requirements to restore North Dakota mined land to original productivity. Soc. of Mining Eng., Salt Lake City, UT, p. 1708–1712.
Power, J.F., F.M. Sandoval, R.E. Ries, and S.D. Merrill. 1981. Effects of topsoil and subsoil thickness on soil water content and crop production on a disturbed soil. Soil Sci. Soc. Am. J. 45:124–129.
Power, J.F., S.D. Merrill, and S.J. Smith. 1985. Effect of soil thickness on nitrogen distribution and use by crested wheatgrass. Soil Sci. Soc. Am. J. 49:1461–1465.
Redente, E.F., C.B. Mount, and W.J. Ruzzo. 1982. Vegetation composition and production as affected by soil thickness over retorted oil shale. Reclam. Reveg. Res. 1:109–122.
Scholl, D.G. 1987. Soil salinity and water movement during irrigation of a topsoil-coal spoil profile. p. 115–121. *In* Proc. 1987 Natl. Meeting, Am. Soc. for Surface Mining and Reclamation. Fourth Biennial Symp. on Surface Mining and Reclamation on the Great Plains, Billings, MT. 17–19 March. Am. Soc. for Surface Mining and Reclamation, Princeton, WV.
Sieg, C.H., D.W. Uresk, and R.M. Hansen. 1983. Plant-soil relationships on bentonite mine spoils and sagebrush grassland in the Northern High Plains. J. Range Manage. 36:289–294.
Smith, J.A., G.E. Schuman, E.J. DePuit, and T.A. Sedbook. 1985. Wood residue and fertilizer amendment of bentonite mine spoils: I. Spoil and general vegetation responses. J. Environ. Qual. 14:575–580.
Steel, R.G.D., and J.H. Torrie. 1980. Analysis of variance: IV. Split-plot designs and analysis. p. 377–400. *In* Principles and procedures of statistics: A biometrical approach. 2nd ed. McGraw Hill Book Company, New York.
Stoskopf, N.C. 1981. Root growth, seedling development and crop production. p. 369. *In* Understanding crop production. Reston Publ. Co., Reston, VA.
Uresk, D.W., and T. Yamamoto. 1986. Growth of forbs, shrubs and trees on bentonite mine spoil under greenhouse conditions. J. Range Manage. 39:113–117.

Injury and Yield Response of Cotton to Chronic Doses of Ozone and Soil Moisture Deficit[1]

ALLEN S. HEAGLE,* J. E. MILLER, W. W. HECK, AND R. P. PATTERSON

ABSTRACT

Plant response to ozone (O_3) is known to be modified by soil moisture deficit, which occurs in varying degrees during most growing seasons. Thus, we examined the response of cotton (*Gossypium hirsutum* L. 'McNair 235') to different levels of seasonal stress by O_3 when grown at two soil moisture levels. The cotton was exposed for 12 h d^{-1} in open-top field chambers to five O_3 doses (seasonal 12 h d^{-1} means from 0.020 to 0.074 $\mu L\ L^{-1}$) under well-watered (WW) conditions or under water-stressed (WS) conditions with periodic cycles of low soil moisture. Exposures began when the fifth leaves were expanding and continued for 124 d when most leaves were chlorotic or had abscised. Ozone caused significant yield loss in WW plots but not in WS plots. Based on estimates from polynomial regression analysis, ambient O_3 (seasonal 12 h d^{-1} mean of 0.044 $\mu L\ L^{-1}$) caused a yield decrease of 19% in the WW plots compared to the O_3 level in our charcoal-filtered air plots (seasonal 12 h d^{-1} mean of 0.022 $\mu L\ L^{-1}$). The comparable estimate for data from the WS plot was 7%, but this regression was not statistically significant. Results indicate that soil moisture deficit can decrease the impact of O_3 on cotton yield.

Yield of cotton (*Gossypium hirsutum* L.) can be decreased by levels of ozone (O_3) that regularly occur in cotton-growing areas. Two experiments compared yield of cotton grown in air where O_3 was partly removed by charcoal filtration (CF) with yield in nonfiltered (NF) air. A greenhouse study in Beltsville, MD, showed that yields of 'Acala SJ-1', 'Stoneville 213' and 'Deltapine smooth Leaf' in NF air were 12, 14, and 31% less, respectively, than yields in CF air (8). Results with 'Acala SJ-2' exposed in field chambers in the San Joaquin Valley of California (1) were similar to those for Acala SJ-1 and Stoneville 213 in Maryland. These studies each showed the amount of yield loss caused by one ambient seasonal O_3 dose but did not allow estimates of relationships between cotton yield and the range of O_3 levels likely to occur in cotton-growing areas.

Two recent studies were performed to measure yield

A.S. Heagle, USDA-Agricultural Research Service, Dep. of Plant Pathology, North Carolina State Univ., Raleigh, NC 27695; J.E. Miller, USDA-ARS, Dep. of Crop Science, North Carolina State Univ.; W.W. Heck, USDA-ARS, Dep. of Botany, North Carolina State Univ.; and R.P. Patterson, Dep. of Crop Science, North Carolina State Univ. Cooperative investigations of the USDA-ARS and the North Carolina State University. Paper no. 11311 of the Journal Series of the North Carolina Agricultural Res. Serv., Raleigh, NC 27695-7601. Research partly supported by an interagency Agreement between the Environmental Protection Agency and the USDA; Interagency agreement number AD-12-F-1-490-2.

Published in J. Environ. Qual. 17:627–635 (1988).

[1]The use of trade names in this publication does not imply endorsement by the North Carolina Agricultural Research Service or the USDA of the products named, nor criticism of similar ones not mentioned. Although the research described in this article was partly funded by the U.S. EPA, it has not been subjected to the EPA's paper and policy review and may not reflect the views of the Agency.

NTIS is authorized to reproduce and sell this report. Permission for further reproduction must be obtained from the copyright owner.

response of cotton to a range of O_3 concentrations in open-top field chambers. At Shafter, CA, yield of Acala SJ-2 was reduced 15 to 20% at ambient levels of O_3 and 45 to 65% by levels of O_3 that averaged twice as high as ambient (11). At Raleigh, NC, yield of Stoneville 213 was decreased 11% by ambient O_3 levels and 55% by O_3 levels twice as high as ambient (5).

Among all factors that may alter plant response to O_3, the degree of soil moisture availability could be the most important. Greenhouse experiments have generally shown that plants under moisture stress develop less O_3-induced foliar injury from short-term exposure than plants given adequate water (7). Soil moisture deficit induces stomatal closure, thereby decreasing gas exchange between leaves and air. Decreased response to O_3 could occur because less O_3 enters the leaves.

Three reports addressed the effects of moisture stress on yield response to O_3 with field-grown crops. In the cotton study at Shafter, CA, a decreased response to O_3 occurred for plants with suboptimum irrigation in a typically hot and dry season but not in an abnormally cool and wet season (11). Heggestad et al. (9) suggested that moderate moisture stress increased the sensitivity of 'Corsoy' soybean [*Glycine max* (L.) Merr.] to ambient levels of O_3 but decreased the sensitivity to higher levels of O_3. Yield of 'Davis' soybean was decreased by O_3 when plants were well-watered but no yield response to O_3 occurred when plants were grown under severe moisture stress (4). However, moderate moisture stress resulted in an O_3 dose-yield response relationship that was similar to that for plants grown with adequate soil moisture (4).

Estimates of crop loss due to O_3 have been based on O_3 dose-yield response relationships derived from field research with plants grown under optimum soil moisture conditions. Soil moisture effects on crop response to O_3 are complex (4, 7, 9, 11) and further research is needed. Our objective was to measure the effects of chronic doses of O_3 on injury, yield, and quality of an eastern cotton cultivar grown under well-watered and water-stressed conditions.

MATERIALS AND METHODS

The experiment was performed during 1985 in a field located approximately 8 km south of Raleigh, NC. The soil consisted of approximately 30 cm of loamy sand topsoil obtained from a field of Norfolk soil (fine-loam, silicious, thermic Typic Paleudult) overlaying an Appling sandy loam (clayey, kaolinitic, thermic Typic Hapludult). The field was limed and fertilized according to soil test recommendations. For weed control, trifluralin (*a,a,a*-trifluoro-2,6-dinitro-*N,N*-dipropyl-*p*-toluidine) 4EC was applied at 1.2 L ha^{-1} before planting and fluometuron [1,1-dimethyl-2(*a,a,a*-trifluoro-*m*-tolyl) urea] 80 WP was applied at 1.1 kg ha^{-1} before planting.

Cotton ('McNair 235') was planted on 29 May in three-row strips (oriented north-south) with rows spaced 0.5 m apart. Temik TSX 10G, a combination of 5% aldicarb [2-methyl-2(methylthio) propionaldehyde *O*-(methylcarbamoyl) oxime] + 10% PCNB (pentachloronitrobenzene) + 2.5% Terrazole (5-ethoxy-3-trichloromethyl-1,2,4-thiadiazole) was applied at a rate of 16 kg ha^{-1} in a furrow adjacent to each row at planting to control thrips and seedling and root disease. Peak plant emergence occurred on 5 June. Twenty-four plots, each containing three 3-m rows, were chosen on 11 June based on plant stand and size. Plants were thinned to 11 plants m^{-1} row on 11 June. Plants in the center row and in 75 cm of the south half of the remaining two rows were removed in biweekly harvests to determine effects on growth rate, biomass partitioning, and carbohydrate metabolism (results reported elsewhere). Plants in the center row were removed before canopy closure. Insects and mites were controlled with recommended rates of synthetic pyrethrins between 12 July and 12 September; there were three applications of Pounce [3-phenoxybenzy(1RS, 3RS: 1RS,3SR)-3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropane carboxylate (approx. 60% trans, 40% cis isomers)] 3.2 E and five applications of Capture (polyacrylamide) 2EC. Mites were also controlled with one application of dimethoate 2-E [*O,O* dimethyl *S*-(*N* methylcarbamoylmethyl) phosphorodithioate] at a rate of 6.3 mL L^{-1} on 24 July.

Ozone and Soil Moisture Treatments

Frames for open-top field chambers (3) were installed on 20 of the treatment plots on 18 June. Clear polyvinyl chloride film panels were attached on 28 June and the chamber fans were run daily between 0500 and 2100 h EST from 28 June to 11 November. The experiment was a completely randomized factorial design with five O_3 levels in open-top chambers and two soil moisture levels with two replicates (plots) for each O_3-moisture combination. Two replicates of an ambient air (AA) treatment (no chamber) for each moisture level were included. The five chamber treatments were charcoal-filtered (CF) air, nonfiltered (NF) air without added O_3, and three NF treatments with O_3 added in different proportions of ambient O_3 using dispensing and monitoring methods described previously (6). The three proportional treatments were approximately 1.2, 1.4, and 1.7 times ambient O_3 (NF × 1.2, NF × 1.4, and NF × 1.7). Ozone additions were made from 0800 to 2000 h EST when the ambient O_3 concentration exceeded 0.03 $\mu L\ L^{-1}$, except when systems malfunctioned or during calibration of monitoring tubes (a total of 4.4% of the possible dispensing time). Ozone additions began on 28 June when plants were approximately 20 cm tall and had an average of four expanded leaves. Ozone additions ended on 30 October when leaves in all plots were mostly chlorotic or had abscised.

The two soil moisture treatments were established by differential irrigation during periods of low rainfall. Soil moisture was measured at a depth of 23, 46, and 76 cm in all plots with a neutron probe (CPN Model 503, Campbell Pacific-Nuclear, Pacheco, CA) at a position 20 cm west of the east row and 75 cm south of the chamber frame. The criteria used to determine the need for irrigation were mean soil matric potentials at 23 cm of −0.10 and −0.30 MPa for the well-watered (WW) and water-stressed (WS) plots, respectively. When plots were irrigated, approximately 2.5 cm of water was applied (whole-plot basis) with drip tubing located at the base of plants in each row. Water potential of the third or fourth open leaf (counting down from the growing point) was measured at midday (1100–1300 h EST) during stress cycles with thermocouple psychrometers by the dew point technique. At each measurement date (Fig. 3) two plants were sampled in both replicates of the CF, NF × 1.2, and NF × 1.7 plots for each of the two moisture treatments. Psychrometry chambers similar to those described by Brown and Collins (2) were used. The psychrometers were calibrated against salt solutions of known concentrations.

Response Measurements and Statistical Analyses

Injury and yield measurements were obtained from plants in each of two 1-m rows per plot. A 0.50-m row section between the north end of each row and the chamber wall and a 0.15-m row section at the south end of each row served as border. Foliar injury was estimated visually as the combined percentage

chlorosis and necrosis in 5% increments (0–100%) for all individual leaves arising from the main stem of three plants per plot. Abscised leaves were rated as 100% injured. Injury estimates were made on 15 July, 3 and 23 September, and 11 October using randomly selected plants at each date. In this, as in previous work, it was not feasible to determine the precise cause of chlorosis, necrosis, and abscission for individual plants. We assume that the amount of O_3-induced injury was the difference between estimated injury in the CF plots (not O_3-induced) from that in other plots.

Cotton from each of two 1-m rows per plot was hand-picked on 30 September; 7, 15, 24, and 30 October; and 5 November. At each harvest only fluffy locks were picked, and the number of harvested bolls was counted. Seedcotton was placed in paper bags, air-dried to constant weight, and weighed. On 6 November, plant shoots were removed from the field and immature bolls were counted and placed in paper bags. Plant shoots (stems, branches, and empty locules) and immature bolls were dried to a constant weight and weighed. After final harvest, seedcotton from each treatment combination was pooled, a 500-g subsample was ginned, and the percentage (wt. basis) of fiber and seed was determined. Standard market quality analyses were performed for lint and seeds (12).

Analyses of variance (AOV) were performed on total yield (weight of seedcotton per meter of row) and total number of harvested bolls from all plots to determine effects of row position within chambers (position). The position effect was significant for both moisture levels as plants in the east row produced 9 to 11% more bolls and yield than those in the west row. However, the O_3 × position interaction was not significant and plot means were used in subsequent analyses. Analyses of variance were next performed on all measured growth and yield parameters to test for the effects of O_3, soil moisture level, and the interaction. Analyses of variance were also performed to test for O_3 effects for each soil moisture level separately. Lint and seed quality factors were analyzed by AOV for the moisture levels combined.

Polynomial and Weibull (10) dose-response models were fit to the chamber yield data (AA plots excluded) for soil moisture levels separately and combined. In all analyses, the seasonal 12 h d^{-1} mean O_3 concentration for each treatment plot was used as the independent variable. Lack-fo-fit tests were calculated for all models and tests of homogeneity were performed to determine whether moisture level affected the response curves.

RESULTS

Ozone Doses

During the exposure period (28 June–30 October), the mean 12 h d^{-1} O_3 concentration (seasonal mean) in the AA plots was 0.044 $\mu L\ L^{-1}$. Concentrations in the chambered plots (combined for soil moisture treatments and replicates) were 0.021, 0.041, 0.051, 0.061, and 0.073 $\mu L\ L^{-1}$ for the CF, NF, NF × 1.2, NF × 1.4, and NF × 1.7 treatments, respectively (Table 1). The variation in 12 h d^{-1} seasonal mean O_3 concentrations for plots at a given O_3 treatment/moisture level combination was less than 0.003 $\mu L\ L^{-1}$. The highest ambient 1-h peak was 0.119 $\mu L\ L^{-1}$, almost equalling the federal secondary ambient air quality standard for O_3 of 0.120 $\mu L\ L^{-1}$ (Table 1). The 1-h standard was not exceeded in the NF plots but was in all three treatments that received O_3 additions. The daily 12-h and 24-h ambient O_3 concentrations showed the typical pattern of periodic ambient air episodes, each usually lasting 3 to 5 d before dissipating due to changes in weather patterns (Fig. 1). Twelve-hour means of 0.07 $\mu L\ L^{-1}$ or greater occurred on 8 d while the highest 12-h mean was 0.09 $\mu L\ L^{-1}$. The mean-seasonal diurnal O_3 concentration patterns illustrate that the daily 12-h period of O_3 addition coincided well with the daily period of elevated O_3 in ambient air (Fig. 2).

Table 1. Ozone concentrations measured during exposure of 'McNair 235' cotton to O_3 at different soil moisture levels.†

Soil moisture treatment	Ozone treatment	12 h d^{-1} O_3 conc.		1 h d^{-1} peak O_3 conc.‡	
		Seasonal mean	Highest	Seasonal mean	Highest
		$\mu L\ L^{-1}$			
Well-watered	CF	0.020	0.045	0.028	0.062
	NF	0.041	0.094	0.055	0.118
	NF × 1.2	0.050	0.134	0.069	0.166
	NF × 1.4	0.060	0.174	0.086	0.225
	NF × 1.7	0.071	0.217	0.106	0.290
	AA	0.043	0.089	0.057	0.110
Water-stressed	CF	0.023	0.052	0.032	0.061
	NF	0.040	0.098	0.054	0.109
	NF × 1.2	0.051	0.132	0.071	0.162
	NF × 1.4	0.062	0.172	0.090	0.222
	NF × 1.7	0.074	0.223	0.110	0.281
	AA	0.045	0.092	0.059	0.119

† Each value is the mean from two plots except for the CF, NF, and AA values, which are the mean of one plot, for the daily period 0800 to 2000 h EST from 28 June to 30 October 1985.

‡ The 1 h d^{-1} peak value is defined as the largest mean of two consecutive 3-min samples taken at 45-min intervals from 0800 to 2000 h EST.

Soil and Leaf Moisture

Neutron probe readings at the 23-cm depth were used to characterize soil moisture because most of the root biomass was found in the sphere of measurement of the neutron probe at that depth. The soil moisture measurements (Fig. 3) represent the means of eight WW plots and six WS plots. Ten plots were eliminated when calculating the means because they showed spurious readings, probably caused by rocks or other inclusions in the soil. The mean soil matric potential in the WW plots was less than the target minimum (−0.1 MPa) only on 19 July (Fig. 3). This occurred due to the very rapid depletion of moisture in the sandy surface soil due to hot, dry conditions. Monthly climatic factors and irrigation amounts during the experimental period are shown in Table 2. Major periods of low rainfall occurred between 12 and 23 July (0.8 cm of rain), 2 and 16 August (no rain), and 30 August and 22 September (no rain). Irrigation of WW

Table 2. Monthly temperatures, photosynthetically active radiation (PAR), rainfall, and irrigation during the O_3 dose-cotton yield study in 1985.

Variable	Moisture treatment	Month				Total
		July	Aug.	Sept.	Oct.	
Mean max. temp., °C	Both	31.1	30.6	28.5	24.4	
Mean min. temp., °C	Both	20.4	19.2	15.7	13.0	
Mean dew point temp., °C	Both	19.0	17.8	13.3	11.5	
Mean daily PAR, $\mu mol\ m^{-2}\ s^{-1}$	Both	479	449	487	312	
Rain, cm	Both	14.5	9.9	0.9	6.9	32.2
Irrigation, cm	WW†	2.5	7.5	15.0	2.5	27.5
	WS†	0.0	2.5	7.5	0.0	10.0

† WW = well-watered; WS = water-stressed.

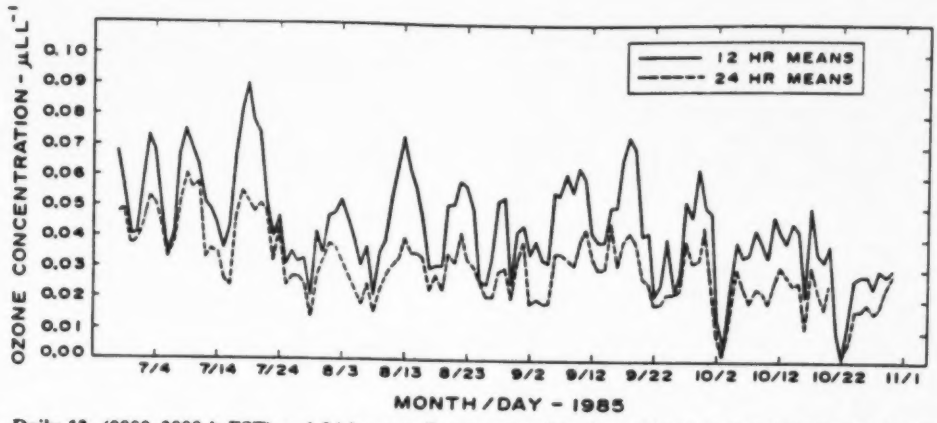


Fig. 1. Daily 12- (0800-2000 h EST) and 24-h mean O_3 concentrations in ambient air from 28 June to 30 October.

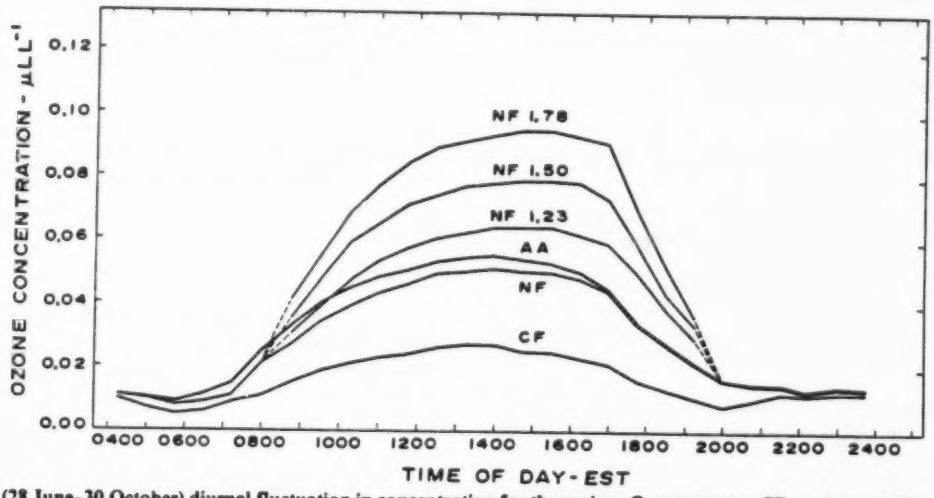


Fig. 2. Seasonal (28 June–30 October) diurnal fluctuation in concentration for the various O_3 treatments. CF = charcoal-filtered air chamber; NF = the common concentration for all nonfiltered air chambers during the period each day when O_3 was not added; AA = ambient air; NF 1.23, NF 1.50, and NF 1.78, = concentrations for nonfiltered-air chambers during the daily 12-h dispensing periods.

Table 3. Mean percentage injury per leaf on 'McNair 235' cotton exposed to different doses of O_3 at two levels of soil moisture.

Soil moisture treatment	Ozone treatment	Seasonal 12 h d^{-1} mean O_3 conc.	Foliar injury per date† 15 July	3 Sept.	23 Sept.	11 Oct.
Well-watered	CF	0.020	2	36	62	71
	NF	0.041	8	46	74	88
	NF × 1.2	0.050	17	59	74	96
	NF × 1.4	0.060	30	56	89	87
	NF × 1.7	0.071	50	66	91	98
	AA	0.043	6	47	79	84
		Means	19	52	78	87
Water-stressed	CF	0.023	1	38	47	51
	NF	0.040	5	44	53	59
	NF × 1.2	0.051	13	53	57	63
	NF × 1.4	0.062	30	57	69	75
	NF × 1.7	0.074	44	59	87	85
	AA	0.045	5	45	82	85
		Means	16	49	66	70

† Each value is the mean estimated chlorosis and necrosis on all main-stem leaves on six plants (three per plot, two replicates). Abscised leaves were rated as 100% injured.

plots was required 11 times (Table 2). Leaf water potential in the WW plots was greater than that in the WS plots each time it was measured (Fig. 3). Values were −2.0 MPa or less on five occasions in the WS plots but only once in the WW plots. Wilting in the WW plots was apparent only on 19 July. Wilting in the WS plots also occurred on 19 July and during each of five periods in which soil matric potential was less than −0.25 MPa (Fig. 3). At four of these times water stress was eliminated by irrigation and on the other by rainfall.

Foliar Injury

For each O_3 treatment at each moisture level, foliar chlorosis and necrosis (injury) increased as the season progressed (Table 3). For a given date, injury generally was greater at each increment in O_3 concentration at both moisture levels. The effects of soil moisture treatment on the amount of foliar injury were slight on 15 July and 3 September. On 23 September and 11 October, more in-

Table 4. Effects of chronic doses of O_3 on number and weight of immature bolls, number of harvestable bolls, weight of seedcotton per harvested boll, cotton yield (seedcotton), and shoot weight.†

Soil moisture treatment	Seasonal 12 h d^{-1} O_3 conc.	Immature bolls			No. of harvested bolls m^{-1}	Seedcotton wt. per boll‡	Seed-cotton, wt. m^{-1}	Empty locule, stem and branch, wt. m^{-1}	Total shoot wt. m^{-1}§
		No. m^{-1}	Wt. per boll‡	Total wt. m^{-1}					
	μL L^{-1}		g			g			
Well-watered	0.020	25	5.8	146	78	5.7	443	430	1019
	0.041	23 (92)	5.6 (97)	128 (88)	77 (99)	5.5 (96)	424 (96)	375 (87)	927 (91)
	0.050	28 (112)	4.8 (83)	134 (92)	66 (85)	5.4 (95)	355 (80)	335 (78)	823 (81)
	0.060	32 (128)	4.3 (74)	139 (95)	66 (85)	4.8 (84)	320 (72)	306 (71)	765 (75)
	0.071	34 (136)	4.2 (72)	144 (99)	53 (68)	4.4 (77)	234 (53)	294 (68)	671 (66)
	(AA) 0.043	36 (144)	5.1 (88)	183 (125)	52 (67)	5.9 (104)	307 (69)	318 (74)	808 (79)
Water-stressed	0.023	26	6.0	154	65	5.7	373	393	921
	0.040	28 (108)	5.7 (95)	161 (105)	62 (94)	5.6 (98)	349 (94)	341 (87)	851 (92)
	0.051	27 (104)	4.5 (75)	120 (78)	70 (106)	5.3 (92)	371 (99)	339 (86)	831 (90)
	0.062	14 (54)	4.2 (70)	58 (38)	66 (100)	5.1 (89)	339 (91)	329 (84)	726 (79)
	0.074	13 (50)	3.2 (53)	43 (29)	64 (97)	4.7 (82)	300 (80)	264 (67)	607 (66)
	(AA) 0.045	37 (142)	5.5 (92)	201 (131)	50 (76)	5.9 (103)	295 (79)	300 (76)	796 (86)

† Each value is the mean of four 1-m sections of row (two from each of two plots). Values in parentheses are percent of the respective CF (lowest O_3) values.
‡ These values were obtained by dividing the total weights by the number of bolls.
§ Total shoot weight is the sum of weights of seedcotton; total immature bolls; and empty locules, stems, and branches.

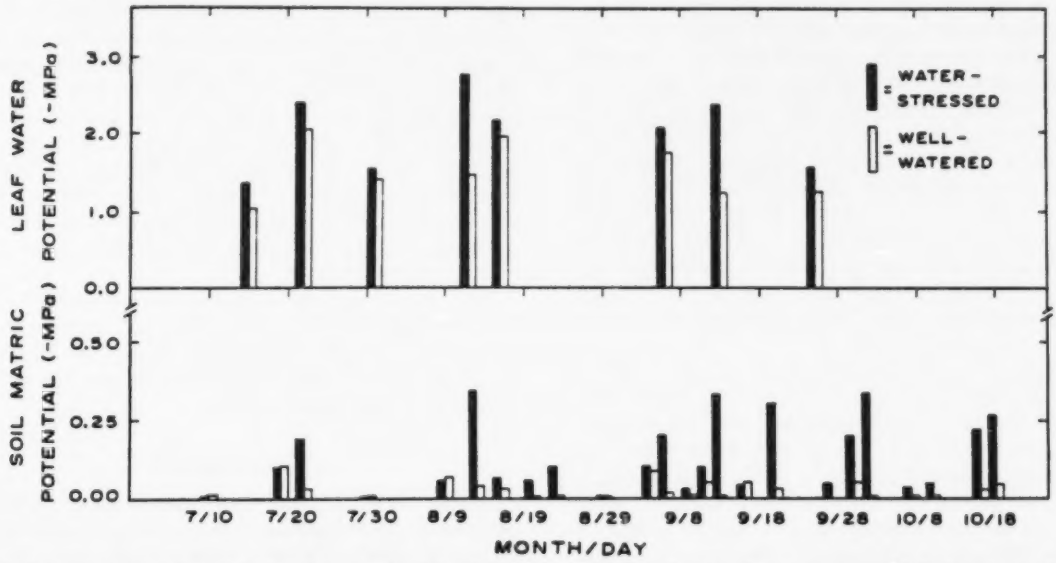


Fig. 3. Soil matric potentials and leaf moisture potentials of water-stressed or well-watered cotton measured during seasonal exposure to chronic doses of O_3.

jury occurred in the WW than in the WS plots for all O_3 treatments (Table 3). Cool weather on 6 to 8 October (mean early morning temperatures of 6–8 C) caused some reddening of leaves. This symptom was most prevalent in AA plots and WW low-O_3 treatment plots.

Growth and Yield

Growth and yield in the AA WS plots were similar to that in the AA WW plots (Table 4). Total shoot weight in the AA plots was similar to that in the chambers with O_3 levels similar to ambient (NF and NF × 1.2 plots). However, there was an apparent chamber effect that decreased the number of immature bolls and increased the number of harvestable bolls and yield. For the chambered plots, shoot weight (stems, branches, empty locules, immature bolls, and seedcotton) per meter of row was usually greater (but not significantly) in the WW than in the WS plots (Table 4). For both soil moisture treatments, the effect of O_3 on total shoot weight (compared to CF) was similar. However, partitioning of biomass to reproductive structures seemed to be affected differently by O_3 in the two soil moisture treatments. The number of immature bolls increased as the O_3 concentration increased in the WW plots but the reverse was true in the WS plots (Table 4). The effect of O_3 in decreasing weight per immature boll appeared to be greater in the WS than in the WW plots (Tables 4, 5). The number of harvested bolls generally decreased with each increase in O_3 concentration in the WW plots but not in the WS plots (Table 4), but the interaction betwen O_3 and moisture was not statistically significant (Table 5).

Table 5. Mean squares and probability levels from analysis of variance for yield (seedcotton weight) number of harvested bolls, seedcotton weight per boll, and weight per immature boll.†

Source	df	Yield‡		Number of harvested bolls		Seedcotton wt. per boll		Weight per immature boll	
		Mean square	*PR* > *F*	Mean square	*PR* > *F*	Mean square	*PR* > *F*	Mean square	*PR* > *F*
				Moisture levels combined					
Ozone	5	11 384	0.011	254	0.113	1.06	0.001	3.72	0.004
Moisture	1	467	0.663	24	0.650	0.04	0.460	0.06	0.760
Ozone × moisture	5	3 048	0.324	101	0.509	0.02	0.919	0.08	0.979
Error‡	12	2 332	-	112	-	0.07	-	0.56	-
				Well-watered plots—separate					
Ozone	5	12 148	0.009	253	0.115	0.63	0.001	1.64	0.059
				Water-stressed plots—separate					
Ozone	5	2 284	0.469	103	0.501	0.45	0.005	2.16	0.026

† Analyses with data from AA plots included. Plot values are means of two 1-m rows per plot. Yield was measured in grams of unginned (seedcotton) per meter of row. Boll number is combined total from all harvests per meter of row.
‡ Pooled estimate of error was used for all *F*-tests because comparison of the error mean square for each moisture level showed no difference.

The AOV showed a significant O_3 effect on yield in the analyses combined over moisture treatments. In analyses for soil moisture treatments separately, the O_3 effect was significant only for the WW plots (Table 5). For the regression analyses combined over moisture levels, the polynomial and Weibull models were both significant when a dummy variable to account for the moisture effect (M) was used (Table 6). The M term was coded as 0 for the WS plot data and as 1 for the WW plot data. The combined polynomial analysis shows an adequate fit with a linear O_3 term, M, and the $O_3 \times M$ interaction term. A higher-order O_3 term was not significant and was not included in the final model. For the separate regression analyses, the polynomial and Weibull models indicated significant yield responses to O_3 only for the WW plots (Table 6).

The weight of seedcotton per meter of row (yield) at the two lowest O_3 concentrations was greater in the WW than in the WS plots; the reverse was true at the three highest O_3 concentrations (Table 4, Fig. 4), although the AOV showed no significant $O_3 \times$ moisture interaction (Table 5). A test of the homogeneity of the O_3 yield response for the two moisture levels indicated a significant $O_3 \times$ soil moisture interaction for the polynomial but not for the Weibull. These results are not inconsistent because the polynomial analysis tested a linear response, whereas the Weibull analysis tested a nonlinear response.

Quality

The combined AOV (not shown) indicated that O_3 significantly decreased micronaire, yellowness (+b), and sugar content, although the trends were not consistent (Table 7). There was a trend toward decreased brightness (Rb-%) as O_3 increased in the WS but not in the WW plots, although the O_3 effect was not significant in the combined AOV. Micronaire and sugar were significantly higher in the WS than in the WW plots. The only significant interaction between O_3 and soil moisture concerning lint quality was for yellowness, but there were no apparent trends to suggest that this result was anything but random (Table 7).

Fatty acids in cottonseed oil were increased by O_3 at both moisture levels (Table 7). The NH_3 content in seeds was greater in the WS than in the WW plots. There were no significant interactions between O_3 and soil moisture concerning seed quality factors.

DISCUSSION

Ozone caused a general increase in foliar injury and decrease in plant biomass and yield as O_3 concentrations increased. Less foliar injury and a smaller yield response to O_3 occurred with WS than with WW cotton (Tables 3–6, Fig. 4). Examination of the injury data in Table 3 shows that the differences between injury in the CF and that in other plots was usually slightly greater in the WW

Table 6. Polynomial and Weibull regression equations for yield (grams of seedcotton m^{-1} of row).†

Polynomial models

Moisture levels combined‡
Yield = 548 − 3998 X − 141 M + 2791 $X M$
(44) (860) (63) (1211)

Well-watered (separate)
Yield = 548 − 3998 X
(54) (1054)

Water-stressed (separate)*
Yield = 407 − 1207 X
(32) (600)

Weibull models

Moisture levels combined‡
Yield = (414 + 13M) $\exp[-(X/0.103)^{3.46}]$
(41) (29) (0.023) (1.69)

Well-watered (separate)
Yield = 452 $\exp[-(X/0.081)^{3.81}]$
(46) (0.009) (1.82)

Water-stressed (separate)*
Yield = 370 $\exp[-(X/0.112)^{4.97}]$
(24) (0.053) (4.80)

* The water-stressed models were not significant; all other models were significant.
† Analysis with ambient air (AA) plots deleted from data. Standard errors for estimates are given in parentheses. X = seasonal 12 h d^{-1} mean O_3 concentration in $\mu L\ L^{-1}$. The Weibull model is: estimated yield = $\alpha \exp[-(X/\sigma)^c]$; X is the seasonal 12 h d^{-1} mean O_3 concentration; α is maximum yield at 0 $\mu L\ L^{-1}$ O_3; σ is the O_3 concentration at which α is reduced by 63% and c is a dimensionless shape parameter.
‡ M = 1 in well-watered and 0 in water-stressed plots. M was not significant in these models but was left in because the interaction terms were significant.

Table 7. Effects of chronic doses of O_3 on lint and seed quality factors for cotton grown at two levels of soil moisture.†

Soil moisture treatment	Seasonal 12 h d^{-1} mean O_3 conc.	Lint								Seeds			
		Lint in seed-cotton¶	HVI Upper half mean§	1/8-inch gauge		Micro-naire‡	Color		Sugar‡	NH‡	Oil§	Fatty acids in oil‡	100-seed wt., g¶
				Strength§	Elong§		Bright-ness‡ (Rb-%)§	Yellow-ness (+b)					
	μL L^{-1}	%	inches		%						%		
Well-watered	0.020	43	1.17	28.0	7.6	4.2	79.0	9.3	0.28	3.55	22.3	0.3	10.4
	0.041	41	1.16	28.0	7.1	4.6	78.8	9.2	0.32	3.70	21.7	0.3	10.1
	0.050	40	1.18	29.5	6.8	4.0	79.0	9.2	0.26	3.84	21.7	0.4	10.4
	0.060	38	1.16	27.5	7.2	3.8	80.2	8.8	0.24	4.19	19.5	0.4	10.2
	0.071	37	1.15	28.5	7.3	3.6	78.2	9.1	0.24	4.17	18.4	0.5	9.3
(AA)	0.043	40	1.13	26.5	7.0	4.2	76.8	8.7	0.24	3.34	22.0	0.3	10.1
Water-stressed	0.023	40	1.15	27.5	7.1	4.6	79.0	9.2	0.30	4.37	20.5	0.3	10.5
	0.040	41	1.16	28.0	7.0	4.6	79.5	8.6	0.40	3.97	21.2	0.3	11.1
	0.051	40	1.19	30.5	6.9	4.3	78.0	9.6	0.31	4.33	20.9	0.3	10.6
	0.062	40	1.12	28.5	6.9	4.5	77.8	9.2	0.24	4.39	20.3	0.3	10.2
	0.074	38	1.15	28.0	7.8	3.7	73.8	8.4	0.26	4.54	19.5	0.5	10.0
(AA)	0.045	40	1.14	27.0	6.7	4.1	76.0	9.1	0.25	3.74	21.6	0.4	10.3

† Each value is the mean of two samples (1 $plot^{-1}$). Descriptions of lint quality characteristics are contained in reference 12.
‡ Analyses of variance showed a significant O_3 effect.
§ Analyses of variance showed no significant O_3 effect.
¶ Not analyzed statistically.

than in the WS plots. A few exceptions to this trend occurred when the percentage injury exceeded 75% (Table 3). Cause and effect interpretations from injury estimates on 11 October were confounded by low temperature on 6 to 8 October, which appeared to cause more leaf reddening in the WW CF, NF, and NF + 1.2 plots than in other plots. The mechanisms involved in differences between the WW and WS plots were not identified, although it is widely assumed that soil moisture deficit causes decreased stomatal aperture, thereby decreasing O_3 uptake and the amount of injury. It is also possible, however, that plants in the WS plots were less responsive to a given amount of absorbed O_3 than those in the WW plots, although theories on physiological mechanisms for this possibility have not been advanced.

The soil moisture treatment affected the way plants responded to O_3. In WW plots there was a trend for O_3-suppression of the number of harvestable bolls and for decreased weight of seedcotton per harvested boll (boll size) as O_3 increased. This combination of effects also occurred previously with Stoneville 213 (5). However, O_3 suppressed only boll number for Acala-SJ2 in both WW and WS plots (11). In the present study, the O_3 effect on yield for WS plots was caused only by decreased boll size as the number of harvested bolls remained relatively constant across O_3 levels. Plants in WS plots apparently used more available energy for boll maturation in response to increased O_3, whereas the reverse was true for the WW plots. For example, in the WS plots, the percentage of total bolls represented by immature bolls decreased from

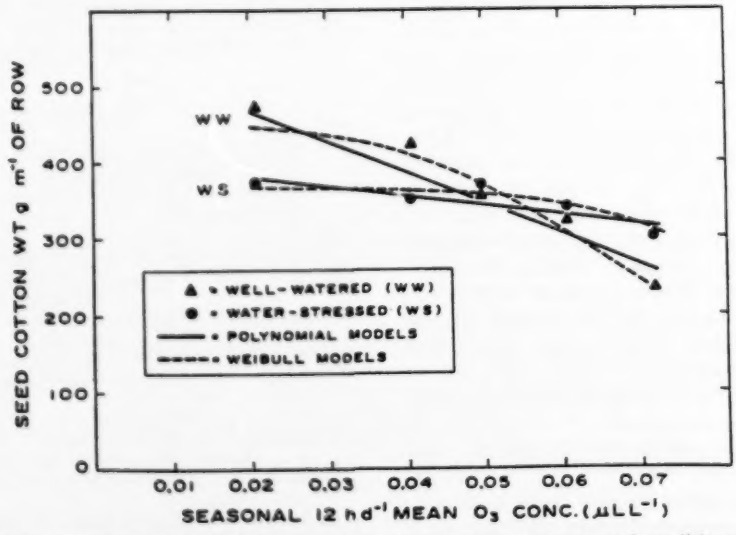


Fig. 4. Effects of O_3 on weight of seedcotton for plants grown under well-watered or water-stressed conditions as predicted by polynomial and Weibull analyses. Measured values (▲ and ●) are the means of two plots.

28% in the CF treatment to 17% in the NF × 1.7 treatment (Table 4). In the WW plots, the percentage of immature bolls increased from 24% in the CF treatment to 39% in the NF + 1.7 treatment. Soil moisture deficit also decreases the rate of evaporative cooling at the soil surface so air temperature in the WS plots was probably slightly higher (1–2 °C) than in the WW plots on sunny days when differences in soil moisture occurred. Thus, it is not known whether the observed effects of soil moisture deficit on O_3 response were direct or were mediated through effects on air temperature. Plants in the AA plots had fewer harvestable bolls and more immature bolls than plants in the NF or NF × 1.2 plots (Table 4). This was possibly due to slightly greater temperatures in chambers, which caused an increased boll maturation rate. While the moisture treatment affected growth and yield in the chamber plots, this did not occur in the AA plots. Possibly, more moisture stress occurred for plants in the WS chambered plots than in the WS AA plots because of slightly higher temperature and less dew formation in chambers than in the AA plots. We did not measure numbers of squares and flowers in this experiment. Thus, differences in the number of immature bolls at the end of the experiment may have been caused by suppressed production of flowers or by an increased rate of abscission of flowers or immature bolls in the WS than in the WW plots.

In this experiment, plots for all O_3 treatments within each moisture treatment were irrigated with the same amount of water on the same days. Thus, within each moisture treatment, there may have been intermittent differences in soil moisture deficit caused by greater moisture use of plants in the low O_3 treatments than in the high O_3 treatments. We recognized this potential but did not employ differential irrigation within moisture treatments, since soil moisture and plant water potential measurements did not clearly identify differences among O_3 treatments. For most of the season in the present study there were no apparent differences in measured soil matric potential across O_3 levels. For the WW plots we measured a slightly lower soil matric potential at low than at high O_3 levels on two dates in late October. For the WS plots, measured matric potentials were often slightly greater in the NF and NF × 1.2 plots than in the NF × 1.7 plots starting in mid-August. However, variation in measured matric potential between the two replicate AA plots (in each moisture treatment) was greater than that measured across the range of O_3 treatments for both moisture treatments. Thus, we do not know whether these differences in measured soil matric potential among the chambered plots were caused by differences in soil moisture use or by differences in soil homogeneity. There were no trends indicative of differences in leaf moisture potential across O_3 treatments for either moisture treatment at any time during the season.

Comparisons between results in the present and previous studies are difficult because cultivars, climate, exposure duration, and other factors were different. However, polynomial regression equations from each study can be used to compare estimated effects on yield (unginned cotton weight) cause by a seasonal 7 h d^{-1} mean O_3 level of 0.05 $\mu L\ L^{-1}$ compared to an estimated natural background level of 0.022 $\mu L\ L^{-1}$. With these equations and O_3 values, the estimated yield effect for Acala SJ2 in the 1981 California study was −12% for WW plots and + 4% for the WS plots (11). Water stress in that study decreased yields in the CF treatment by 43%. For Acala SJ2 in California in 1982, there was no O_3 × soil moisture interaction and the estimated yield effect at 0.05 $\mu L\ L^{-1}$ for the WW and WS plots combined was −15% (11). Water stress in the 1982 California study decreased yields in the CF treatment by 12% (11). Soil moisture effects were not studied for Stoneville 213 at Raleigh (all plots were well-watered) and the estimated yield effect at 0.05 $\mu L\ L^{-1}$ O_3 was −20%. Using the combined polynomial equation (Table 6) from the present study, which used 12 h d^{-1} instead of 7 h d^{-1} exposures, the estimated yield effect of 0.05 $\mu L\ L^{-1}$ O_3 (12 h d^{-1} seasonal mean) on McNair 235 was −24% for the WW plots and −4% for the WS plots. Considering the variables involved in the various O_3 dose-cotton yield experiments, the similarities in estimated yield loss caused by 0.05 $\mu L\ L^{-1}$ O_3 under WW conditions (−12–−24%) are rather remarkable. A seasonal 7 h d^{-1} O_3 concentration of 0.05 $\mu L\ L^{-1}$ is a reasonable level to expect each year in most cotton growing areas. If cotton in commercial production responds to O_3 as cotton in open-top chambers does, significant yield loss due to O_3 occurs each year when there is no soil moisture deficit. We know that soil moisture deficit may decrease the effects of O_3 on cotton yield. However, much more research is required to quantify the changes in crop response to O_3 caused by different levels of soil moisture deficit.

ACKNOWLEDGMENT

We thank David Guthrie for advice and equipment used in planting; Susan Corda and Walter Pursley for technical assistance; Robert Philbeck and Van Poole for dispensing and monitoring systems maintenance; Fred Mowry for computer programming and hardware; and Virginia Lesser, Walter Pursley, and Mary Nations for statistical analyses.

REFERENCES

1. Brewer, R.F. 1979. The effects of present and potential air pollution on San Joaquin Valley cotton. Final Rep. ARB Agreement A-7-119-39. California Air Resources Board, Sacramento, CA.
2. Brown, R.W., and J.M. Collins. 1980. A screen-caged thermocouple psychrometer and calibration chamber for measurement of plant and soil water potential. Agron. J. 72:851–854.
3. Heagle, A.S., D.E. Body, and W.W. Heck. 1973. An open-top field chamber to assess the impact of air pollution on plants. J. Environ. Qual. 2:365–368.
4. Heagle, A.S., R.B. Flagler, R.P. Patterson, V.M. Lesser, S.R. Shafer, and W.W. Heck. 1987. Injury and yield response of soybean to chronic doses of ozone and soil moisture deficit. Crop Sci. 27:1016–1024.
5. Heagle, A.S., W.W. Heck, V.M. Lesser, J.O. Rawlings, and F.L. Mowry. 1986. Injury and yield response of cotton to chronic doses of ozone and sulfur dioxide. J. Environ. Qual. 15:375–382.
6. Heagle, A.S., V.M. Lesser, J.O. Rawlings, W.W. Heck, and R.B. Philbeck. 1986. Response of soybeans to chronic doses of ozone applied as constant or proportional additions to am-

bient air. Phytopathology 76:51-56.
7. Heck, W.W., J.B. Mudd, and P.R. Miller. 1977. Plants and microorganisms. p. 437-585. *In* Ozone and other photochemical oxidants. National Academy of Science, Washington, DC.
8. Heggestad, H.E., and M.N. Christiansen. 1983. Effects of air pollutants on cotton. p. 9-32. *In* J.S. Jacobson and A. A. Millen (ed.) Proc. Symp. on the Effects of Air Pollution on Farm Commodities. Washington, DC. February 1982. Izaak Walton League of America, Arlington, VA.
9. Heggestad, H.E., T.J. Gish, E.H. Lee, J.H. Bennett, and L.W. Douglas. 1985. Interaction of soil moisture stress and ambient ozone on growth and yield of soybean. Phytopathology 75:472-477.
10. Rawlings, J.O., and W.W. Cure. 1985. The Weibull function as a dose-response model for air pollution effects on crop yields. Crop Sci. 25:807-814.
11. Temple, P.J., O.C. Taylor, and L.F. Benoit. 1985. Cotton yield responses to ozone as mediated by soil moisture and evapotranspiration. J. Environ. Qual. 14:55-60.
12. U.S. Department of Agriculture. 1982. Cotton testing service: Tests available, equipment and techniques, and basis for interpreting results. Agricultural Marketing Service. USDA-ARS Agric. Handb. 594. U.S. Gov. Print. Office, Washington, DC.

Growth of Cotton under Chronic Ozone Stress at Two Levels of Soil Moisture

JOSEPH E. MILLER,* ROBERT P. PATTERSON, ALLEN S. HEAGLE, WALTER A. PURSLEY, AND WALTER W. HECK

ABSTRACT

Recent field research has shown that ambient concentrations of ozone (O_3) have the potential to reduce yield of a number of economically important crop species. Soil water levels have been shown sometimes to modify the extent of the reduction. The primary emphasis of most of these studies has been on the plant component that represents economic yield. Less emphasis has been placed on characterization of the effects of O_3 on growth of the total plant that ultimately determines yield. In this study, we measured season-long growth of field-grown cotton (*Gossypium hirsutum* L. 'McNair-235') that was exposed to a range of O_3 concentrations at two levels of soil moisture, well-watered (WW) and water-stressed (WS). The cotton was exposed for 12 h d^{-1} throughout the growing season in open-top chambers to five O_3 concentrations that ranged from 0.020 to 0.074 $\mu L\ L^{-1}$ (seasonal mean 12 h d^{-1} concentration). Three cotton plants were sampled from each chamber at 2- to 3- wk intervals during the season, and biomass and growth measurements were made on all major plant parts. Ozone stress reduced leaf and root biomass in particular, while stem tissues were less affected. Partitioning of biomass among plant tissues was affected by O_3 at certain times during the season. Leaf area duration (LAD) was reduced by O_3 in both WW and WS treatments, but changes in the yield/LAD ratio and net assimilation rate indicated that reduced efficiency of leaves also was responsible for yield reductions in the WW plots. Water stress caused fewer significant effects overall than did O_3, although it appeared to reduce the growth of most plant parts, especially at low O_3 concentrations. There were no significant O_3 × water interactions for the growth variables measured.

Ozone (O_3) and water stress are known to affect the yield of cotton. Experiments using open-top chambers to expose cotton to controlled levels of O_3 have shown that yield may be reduced from approximately 7 to 20% by ambient O_3 concentrations that occur in cotton-growing regions when soil moisture is adequate (Temple et al., 1985; Heagle et al., 1986a, 1988). Since soil water is often limiting during the growth of cotton, the effects of water stress and its potential interaction with O_3 stress have also been investigated. The effects of water stress and its interaction with O_3 stress appear to depend on climatic conditions. Temple et al. (1985) found a yield reduction due to water stress and a reduction of the O_3 effect by water stress during a hot and dry season. A repeat of the experiment during a cool and cloudy season indicated no significant effects of water stress and no modification of the O_3 effect by water stress. Heagle et al. (1988) found that moderate water stress (itself causing a 16% decrease in yield at low O_3 concentrations) reduced the severity of the O_3 effect on yield.

While a considerable amount is known concerning the extent to which O_3 influences crop yield, less is understood concerning its effect on growth and development, especially under field conditions. Evaluation of O_3 effects throughout growth and development should contribute to an understanding of the mechanisms through which the stress is expressed and thereby provide a better basis for evaluation of potential yield effects. Ozone effects on plant growth, development, and partitioning of biomass have been studied under controlled-environment conditions with a number of plant species (Miller, 1987). For example, in a greenhouse study with cotton, Oshima et al. (1979) found that O_3 reduced the dry weight of all plant parts, with the largest reductions occurring in roots and bolls. The effects were ascribed to reductions in leaf area, net assimilation rate, and a shift in the allocation of C.

The effects of water stress on growth, development, and biomass partitioning have been studied more extensively than for O_3. Water stress may reduce vegetative

J.E. Miller, Dep. of Crop Science, USDA-ARS, 1509 Varsity Drive, North Carolina State Univ., Raleigh, NC 27606; R.P. Patterson, Dep. of Crop Science, A.S. Heagle, Dep. of Plant Pathology, USDA-ARS, W.A. Pursley, Dep. of Crop Science, and W.W. Heck, Dep. of Botany, USDA-ARS, North Carolina State Univ., Raleigh, NC 27695. Cooperative investigations of the USDA-ARS and the North Carolina State Univ. Paper no. 11473 of the Journal Series of the North Carolina Agric. Res. Serv., Raleigh, NC 27695-7601. Research partly supported by an Interagency Agreement between the USEPA and the USDA; Interagency agreement no. DW-12931347-01. Although the research described in this article was partly funded by the USEPA, it has not been subjected to the USEPA's paper and policy review, and may not reflect the views of the Agency. Received 3 Mar. 1988. *Corresponding author.

Published in J. Environ. Qual. 17:635-643 (1988).

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This article documents research that was conducted under the auspices of the U.S. Environmental Protection Agency (USEPA). As an arm of the government, the USEPA has a paid up, non-exclusive, irrevocable, worldwide license to reproduce, prepare derivative works, and distribute to the public all of the material contained herein, and to grant others acting on its behalf the right to do so. The USEPA grants to the National Technical Information Service, Department of Commerce, the right to act as its agent in the distribution of this material.